AO3k + SCExAO: on-sky wavefront quality and demonstration of novel WFS techniques with the double XAO system

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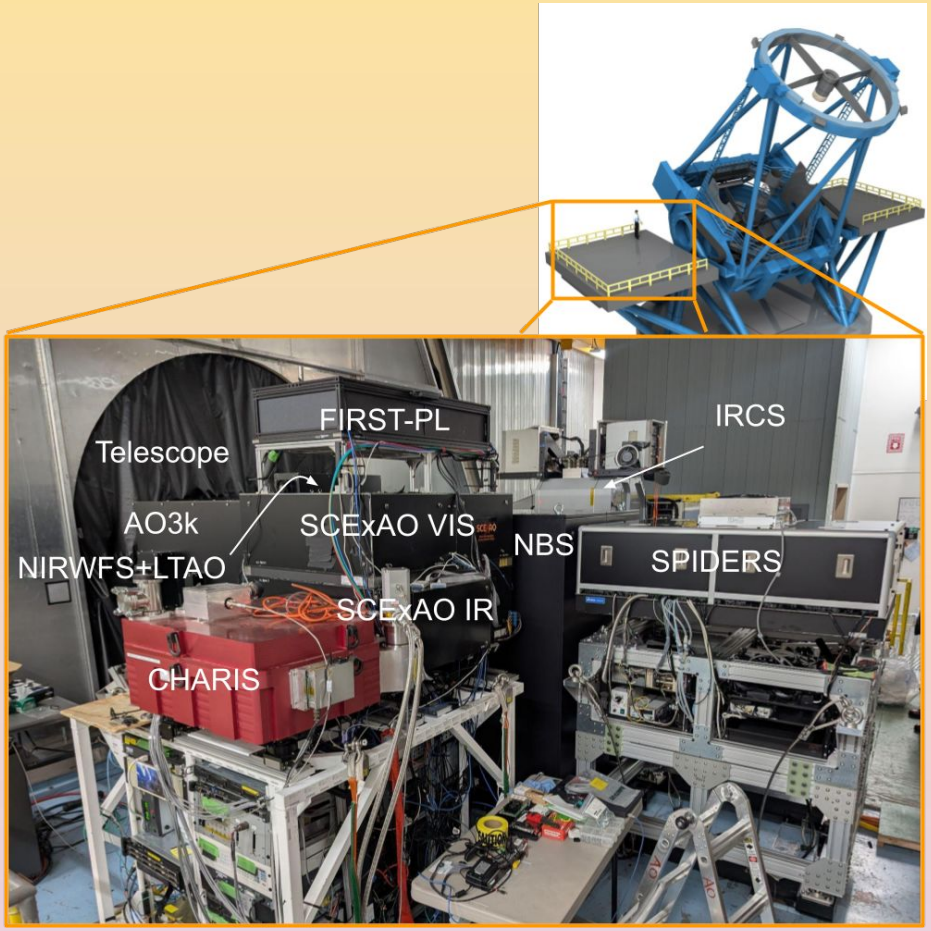
SCExAO Overview

The **Subaru Coronagraphic Extreme Adaptive Optics** platform

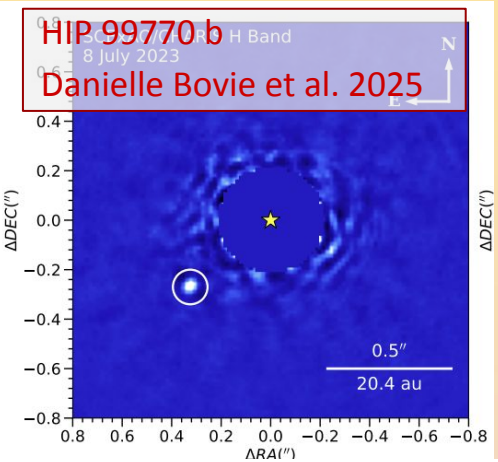
Testbed during the day — **Instrument** during the night

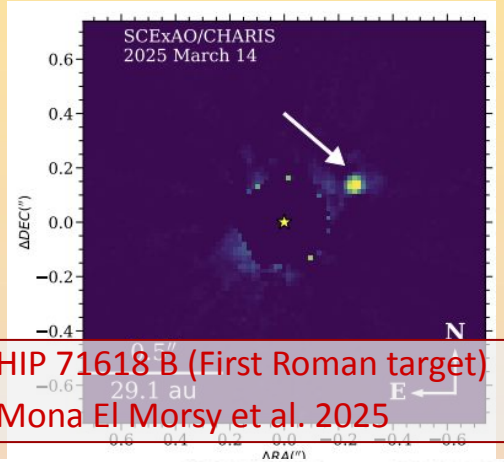
- **At the IR Nasmyth platform of the Subaru Telescope, Maunakea, Hawaii, 4139 m altitude.**
- 50 nights/year (40+ of science)
- Began in 2009 as a Coronagraph+WFS/C demonstrator behind AO188.
- First light in S11A, Science operation started in S14B with HiCIAO (until S17A).
- First Open-Use nights with CHARIS (S17A-), VAMPIRES (S18A-), FPDI (S21B-), MEC (S22A-S24B), FIRST-PL (S26B-)
- Grew to a full high-contrast platform, testing:
  - Wavefront control
  - Coronagraphy
  - Imaging
  - Interferometry
  - Spectroscopy
  - Polarimetry
  - Photonics



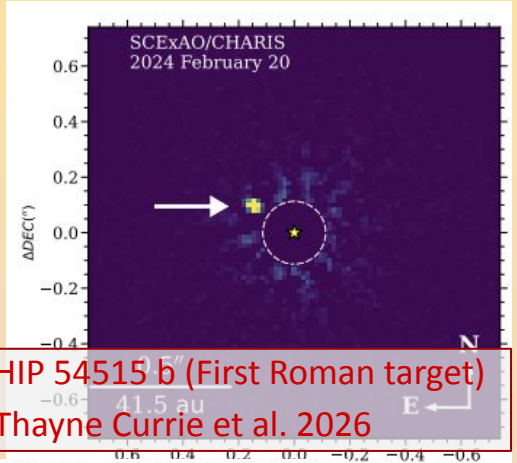
A bit of science

HIP 99770 b
Danielle Bovie et al. 2025



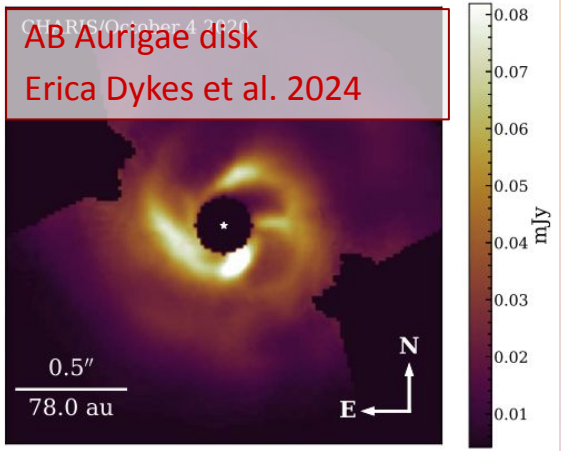


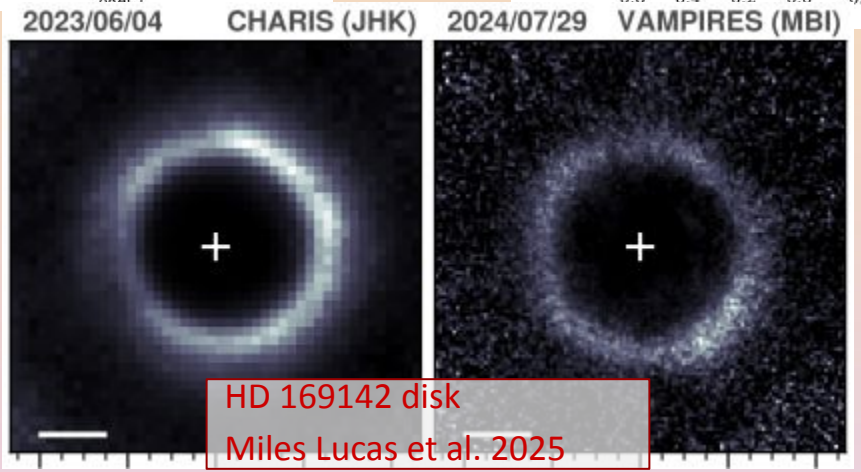
HIP 71618 B (First Roman target)
Mona El Morsy et al. 2025



HIP 54515 b (First Roman target)
Thayne Currie et al. 2026

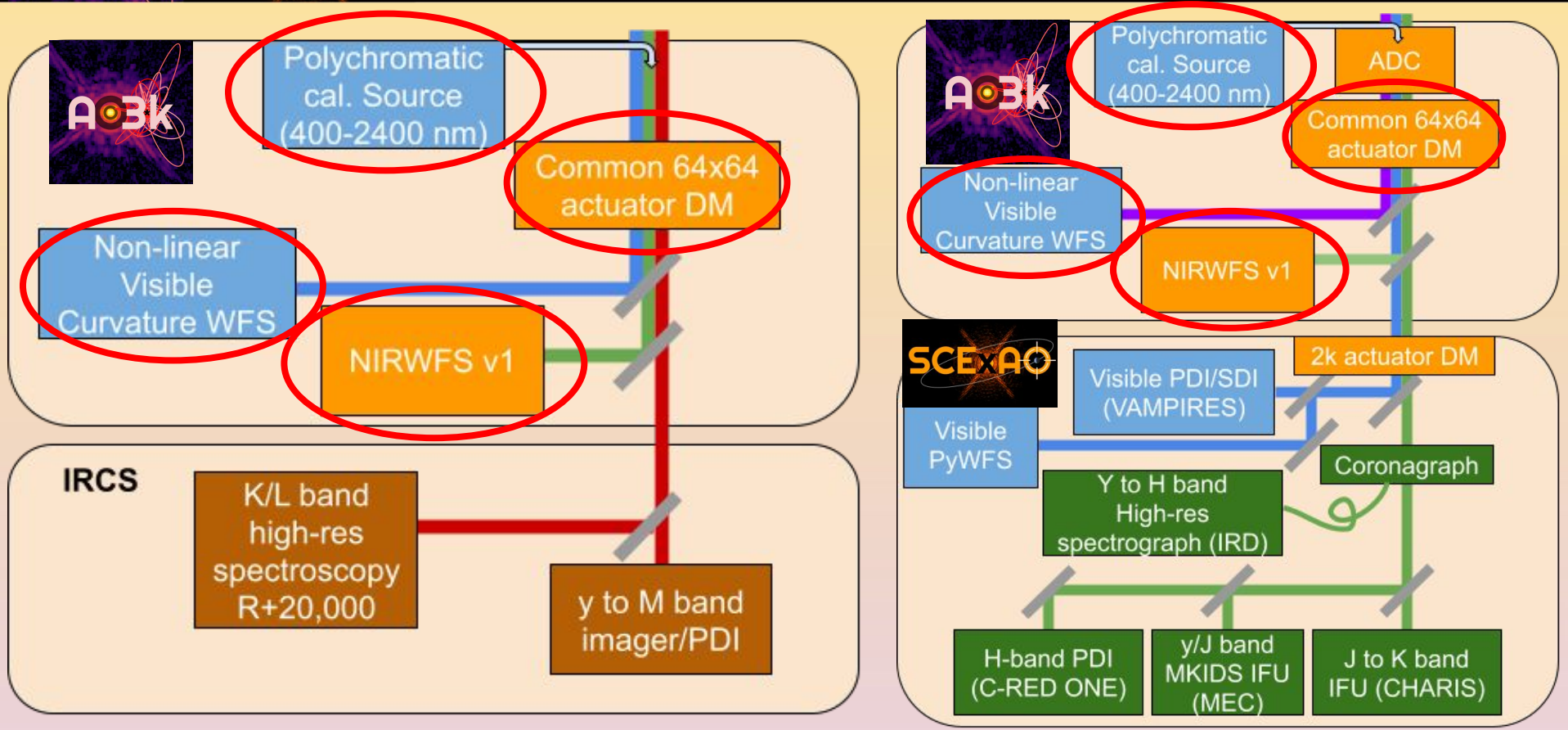
AB Aurigae disk
Erica Dykes et al. 2024



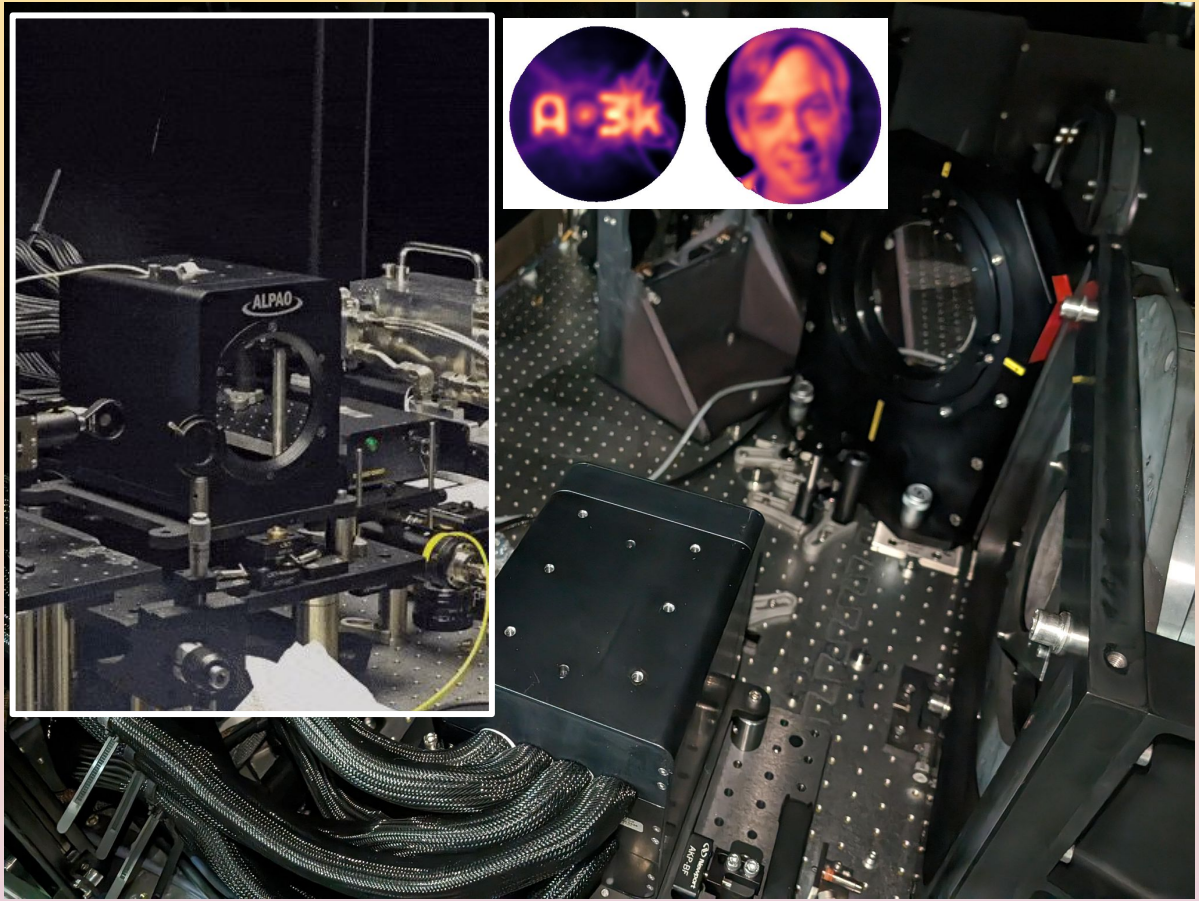


HD 169142 disk
Miles Lucas et al. 2025

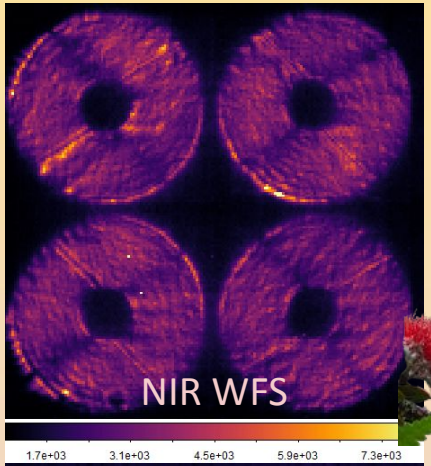
AO3k Phase I (2023-2024)



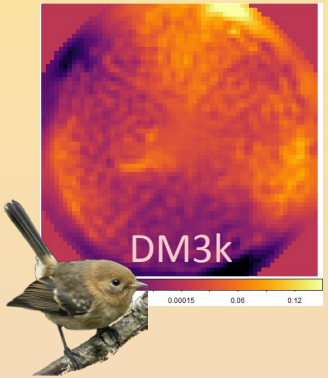
AOM2 TTM & DM3k integration

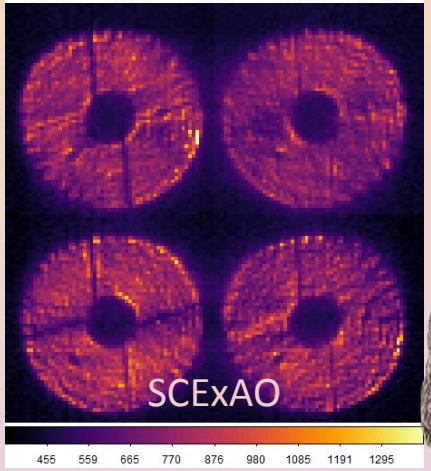


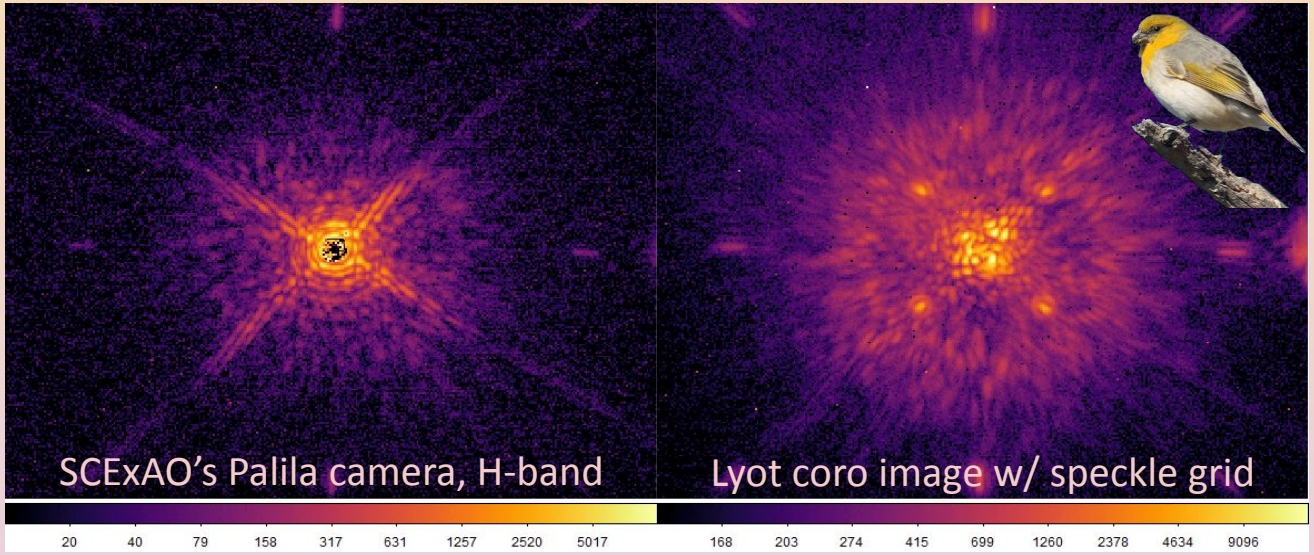
First XAO² on sky



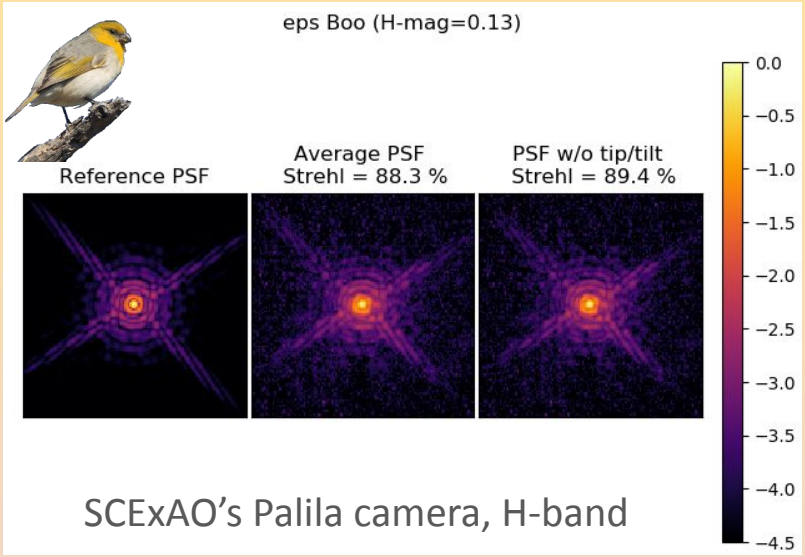
- We closed the loop for the first time with both PyWFS on **Hōkūleʻa (Arcturus, α Boo)** and **Piraʻetea / Hawaiki (Deneb).**
- AO3k's NIR WFS was running at 1 kHz, correcting ~2000 modes
- SCExAO's PyWFS was running at 2 kHz, correcting ~1200 modes
- Some petaling was observed (mostly due to SCExAO),not easily seen by both WFSs, since the NIR WFS wavelength is about 2x the SCExAO PyWFS wavelength.



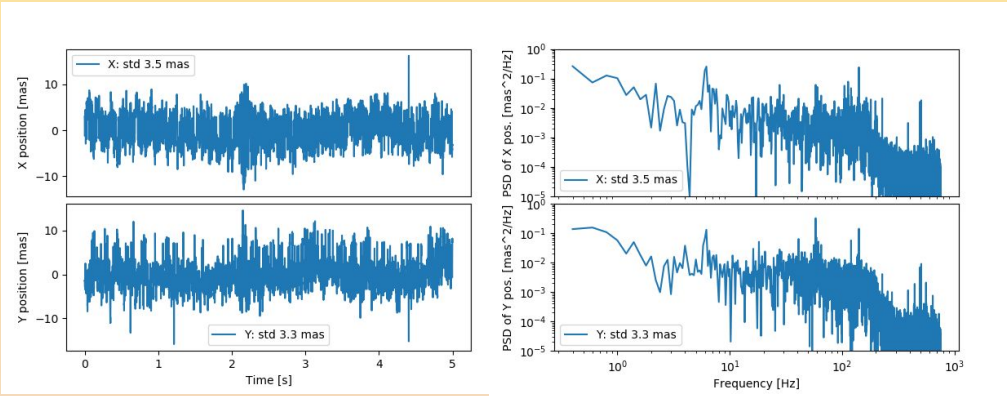




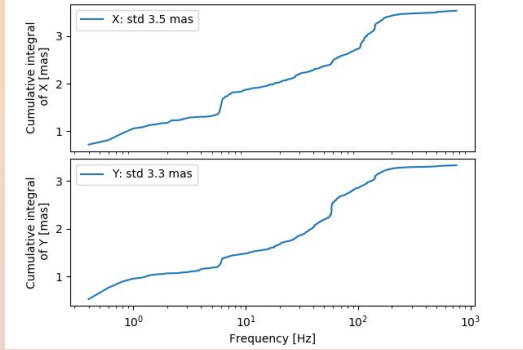
Are we sure it's not the cal source?

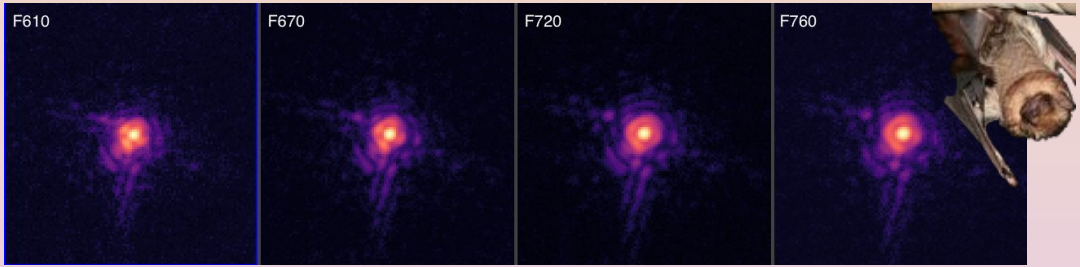


SCExAO's Palila camera, H-band



- We obtained high Strehl, highly stable images.
- The seeing was good/excellent (down to 0.25" at some point!)
- tip/tilt jitter measured @ 1.5 kHz: 2-4 mas!
- Strehl limited by quasi-static low-order modes



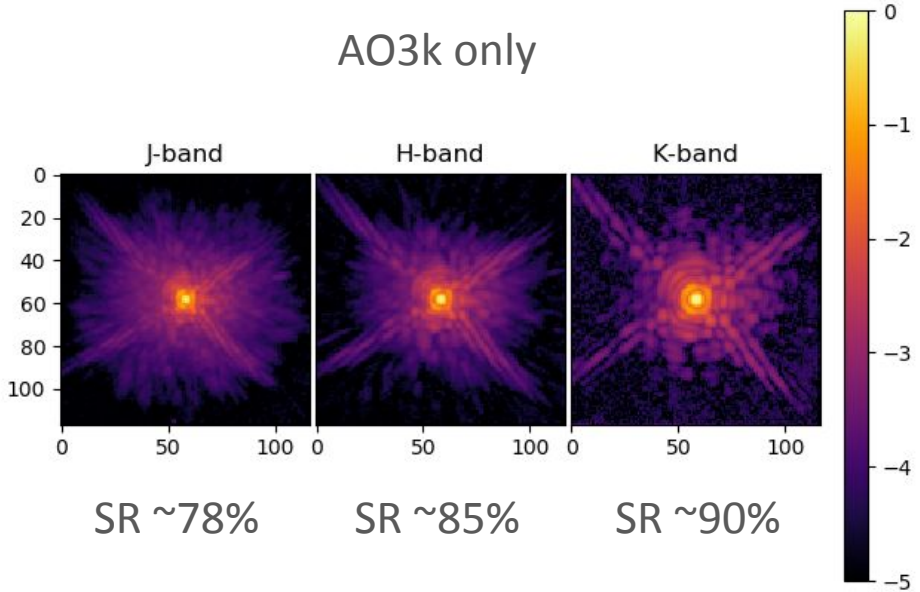


High quality images in visible too w/ VAMPIRES

One or two ExAO?

HD172449 (H-mag=8.18, extinction=0.28, airmass=1.07)

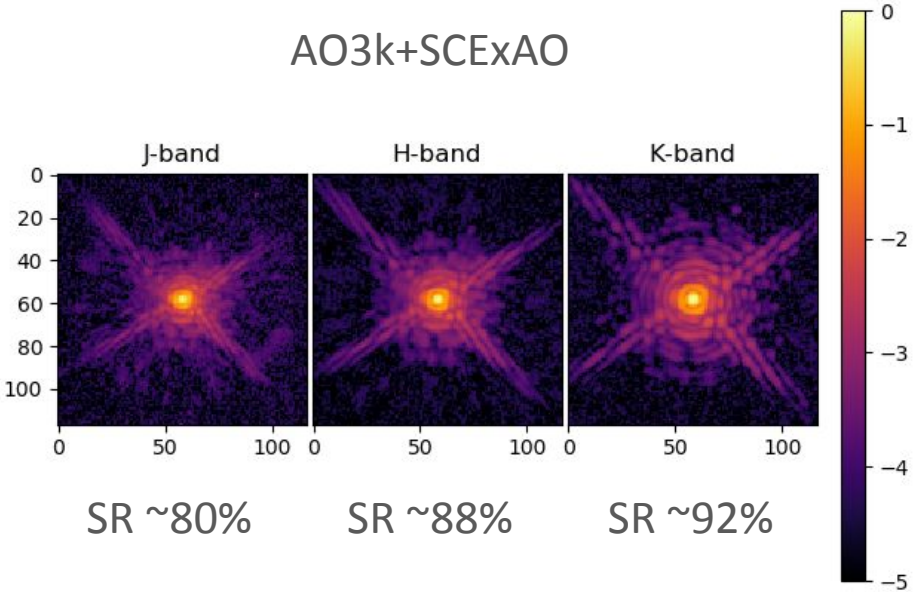
AO3k only



SR ~78% SR ~85% SR ~90%

EPSBOO (H-mag=0.13, extinction=3.13, airmass=1.20)

AO3k+SCExAO



SR ~80% SR ~88% SR ~92%

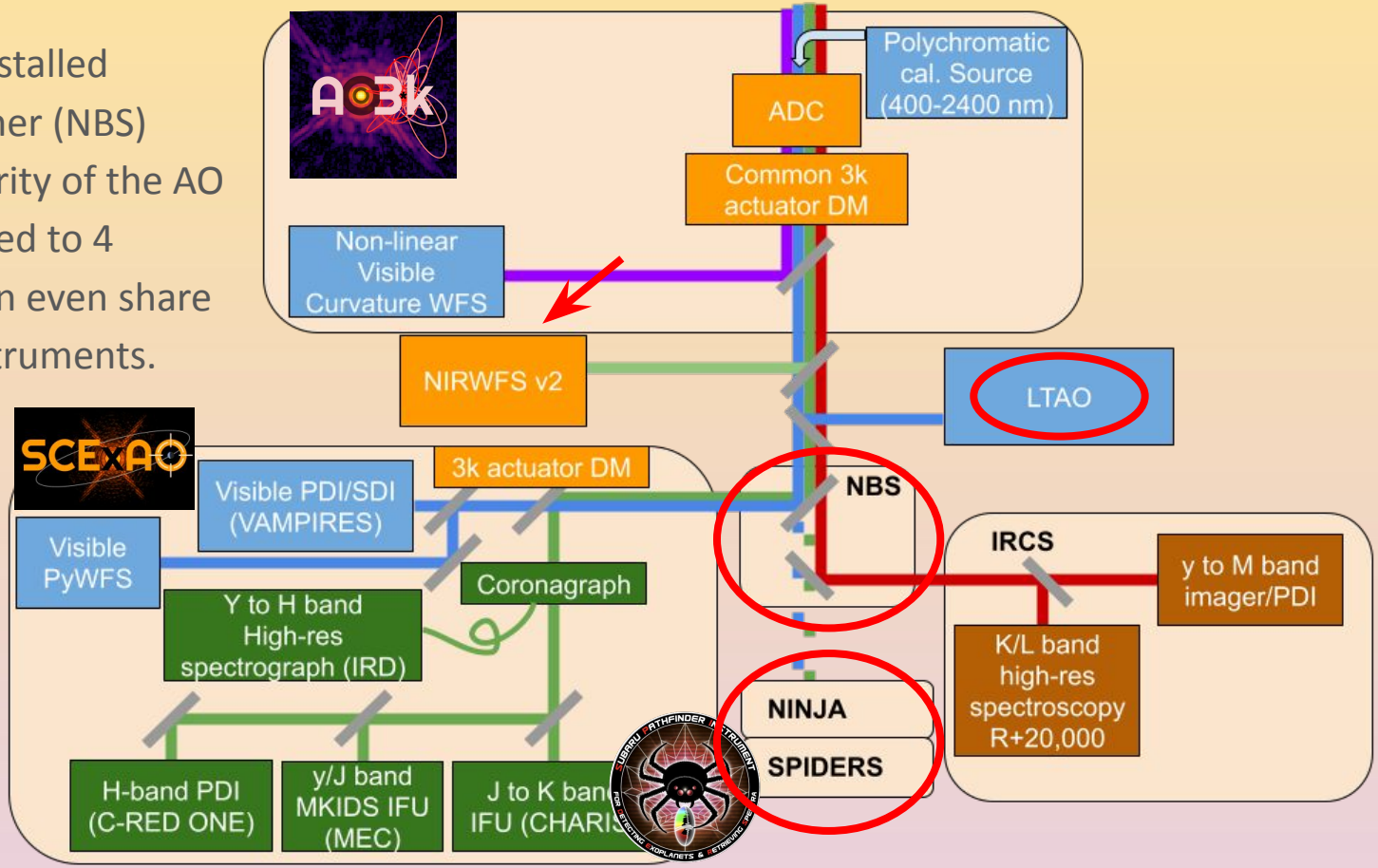
- AO3k provides a high quality PSF thanks to the NIRWFS and the 3000 actuators. This is the PSF feeding IRCS, SPIDERS and NINJA.
- A second layer of ExAO can improve the stability of the speckle field in the case of SCExAO, if there is enough light for the PyWFS.
- In some cases, the second DM could be use for dark hole digging (SPIDERS, SCExAO)

AO3k Phase II (2025)

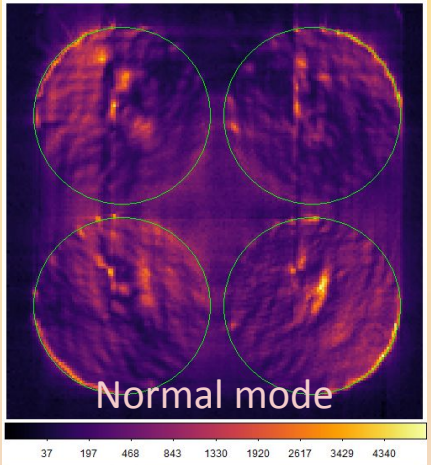
In Phase II, a newly installed Nasmyth beam switcher (NBS) increases the modularity of the AO system. Light can be fed to 4 different ports, we can even share the light between instruments.

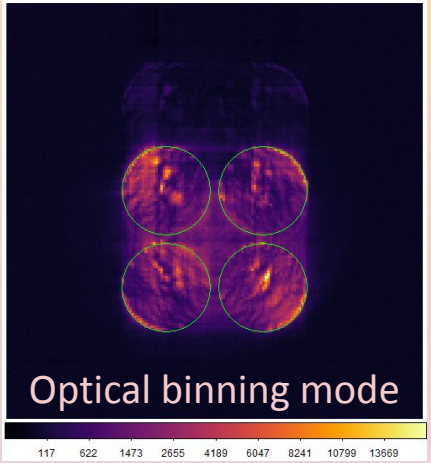
The NIRWFS was upgraded and relocated next to the new LTAO.

SPIDERS was visiting from Nov. 2025 to June 2026, and NINJA will be installed soon.

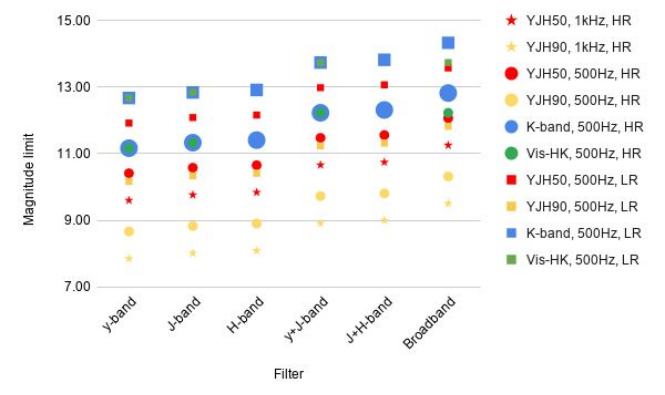


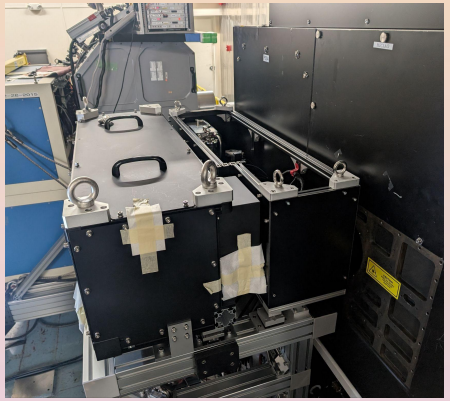
NIRWFS v2

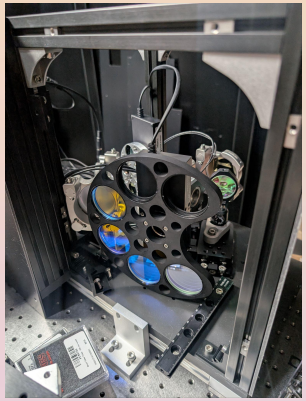




- Version 2 of the NIRWFS was integrated and installed behind AO3k, along with the NBS and LTAO.
- NIRWFS v2 was already used during the commissioning of the NBS and showed similar performances as v1. The optical binning mode allows to increase the magnitude limit by 1.5 mag: mH between 12 and 14.5 depending on the mode and the spectral type of the NGS.
- A new L-band dichroic was also added for IRCS observations.
- NIRWFS v2 combined with the NBS improves the observing flexibility dramatically.

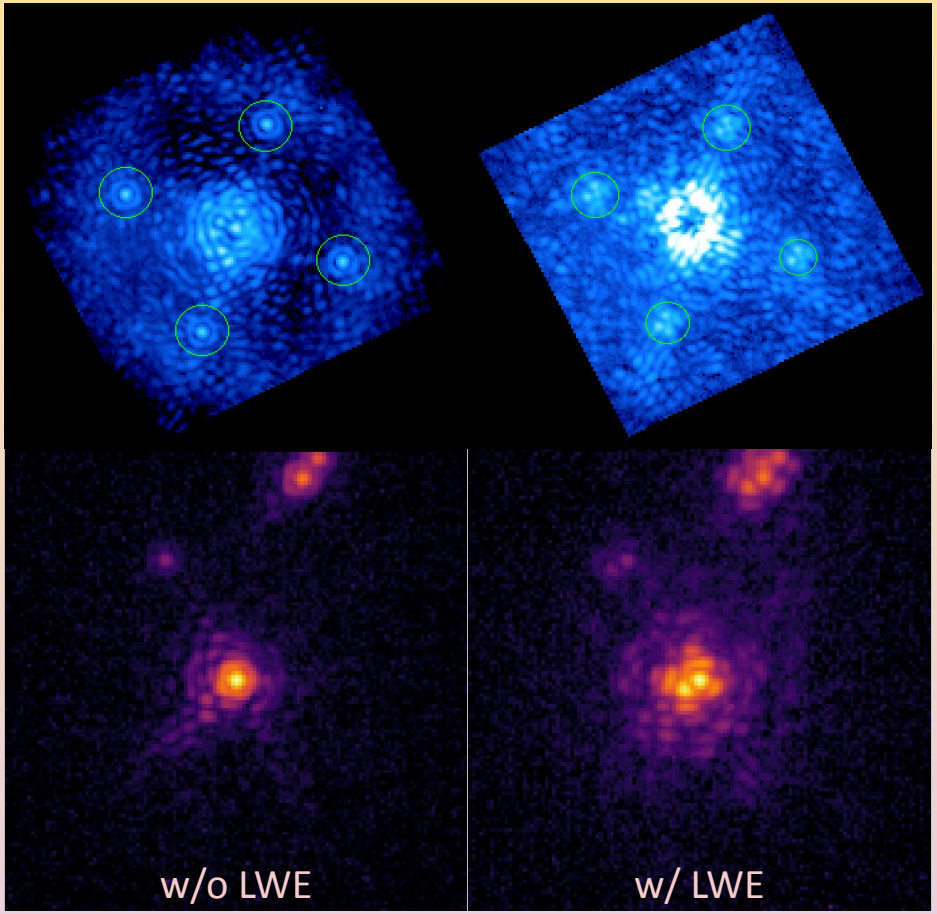






LWE my old friend

- Low-wind effect is still a huge problem, affecting us 30-50% of the time (!!): 1 star can become split into 2, 3 or 4 lobes.
- The petal modes are not well sensed by the NIRWFS, and it can even artificially create these modes, mainly when modal gains are not optimal.
- We are working on several options to manage the petal modes: F&F, 2F2F, LLOWFS, ZWFS, RAP, NRM, GLINT, PL… But there is no easy & unique solution for every observations.

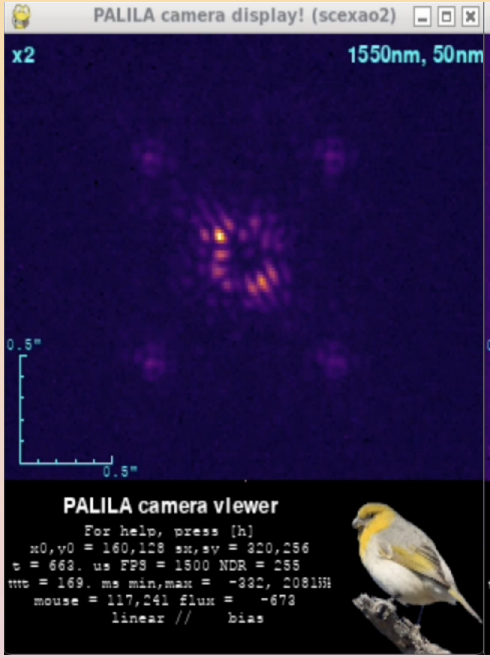


LLOWFS for petal modes

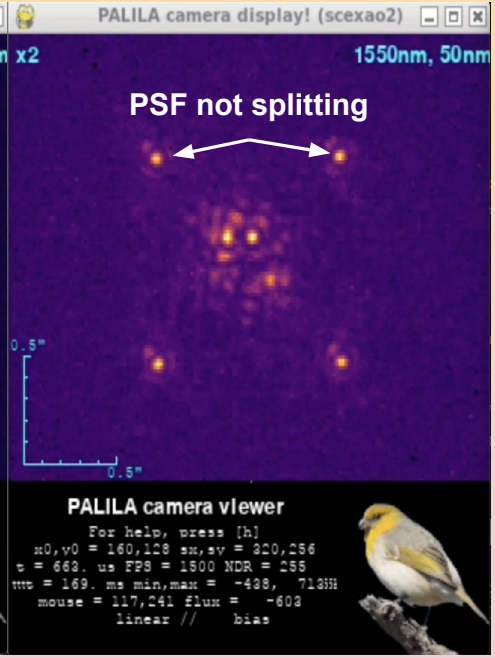
Work led by Garima Singh

On-sky testing with linear algorithm

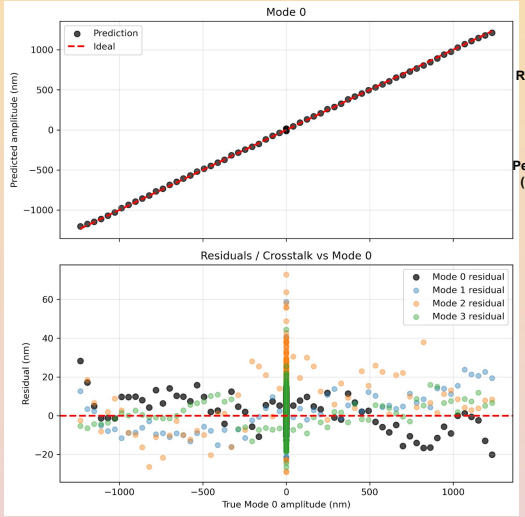
LLOWFS loop open

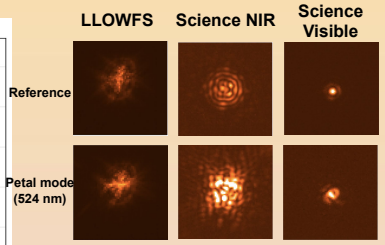


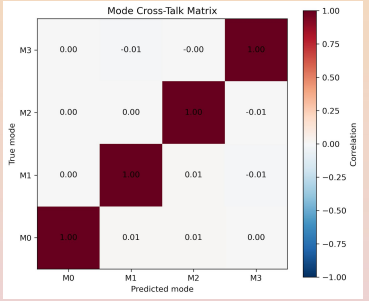
LLOWFS loop closed



Machine learning-based LLOWFS reconstructor (concept tested on the SPIDERS instrument)







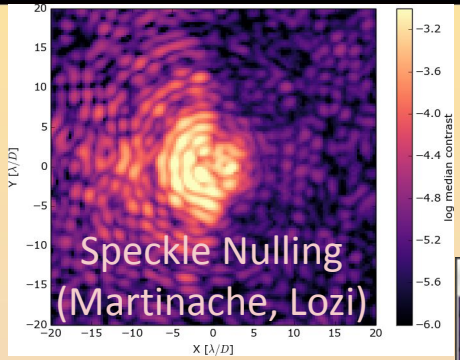
Improved linearity range of LLOWFS (four petal modes), Laboratory, Vortex coronagraph, H-band, Singh et al in prep

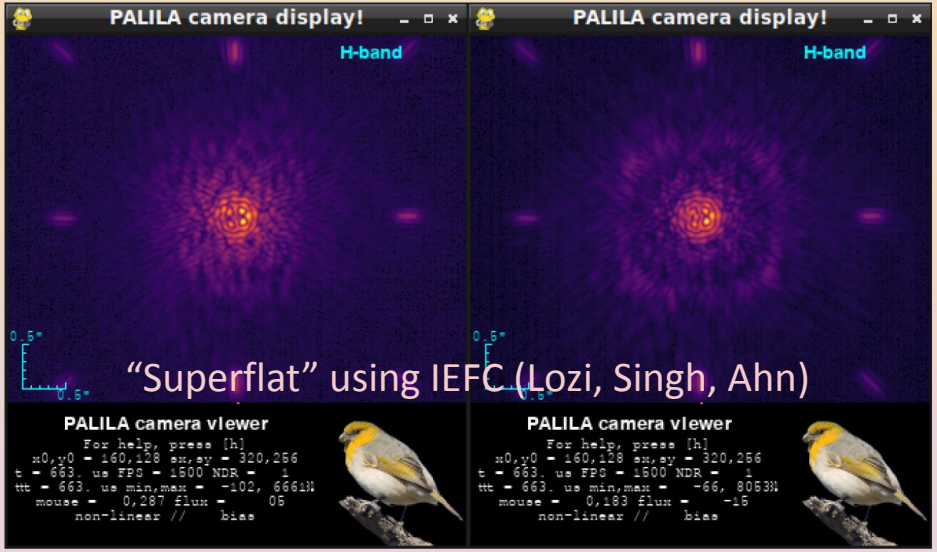
IEFC: improve the contrast

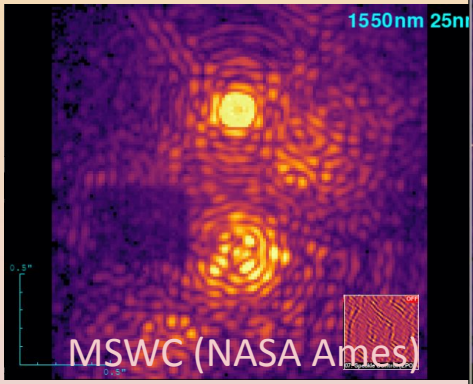
Several algorithms were tested over the years to improve the contrast in the images:

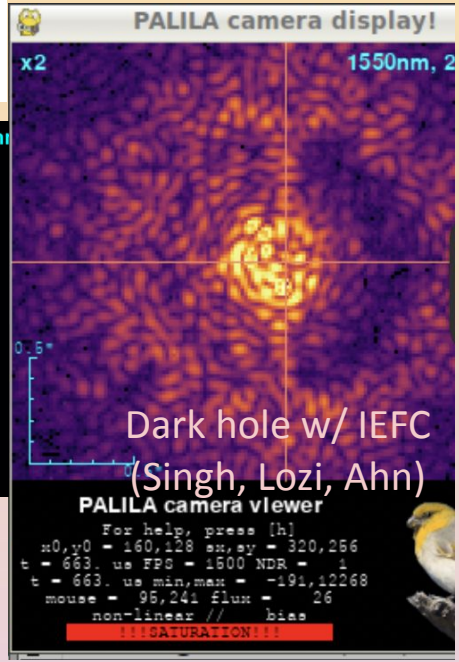
- Speckle Nulling (Martinache et al. 2013)
- Multi-star Wavefront Control (Sirbu et al. 2020)
- IEFC (Ahn et al. 2024)

They can be used to flatten the DMs (SCExAO DM and AO3k DM) and/or create dark holes.





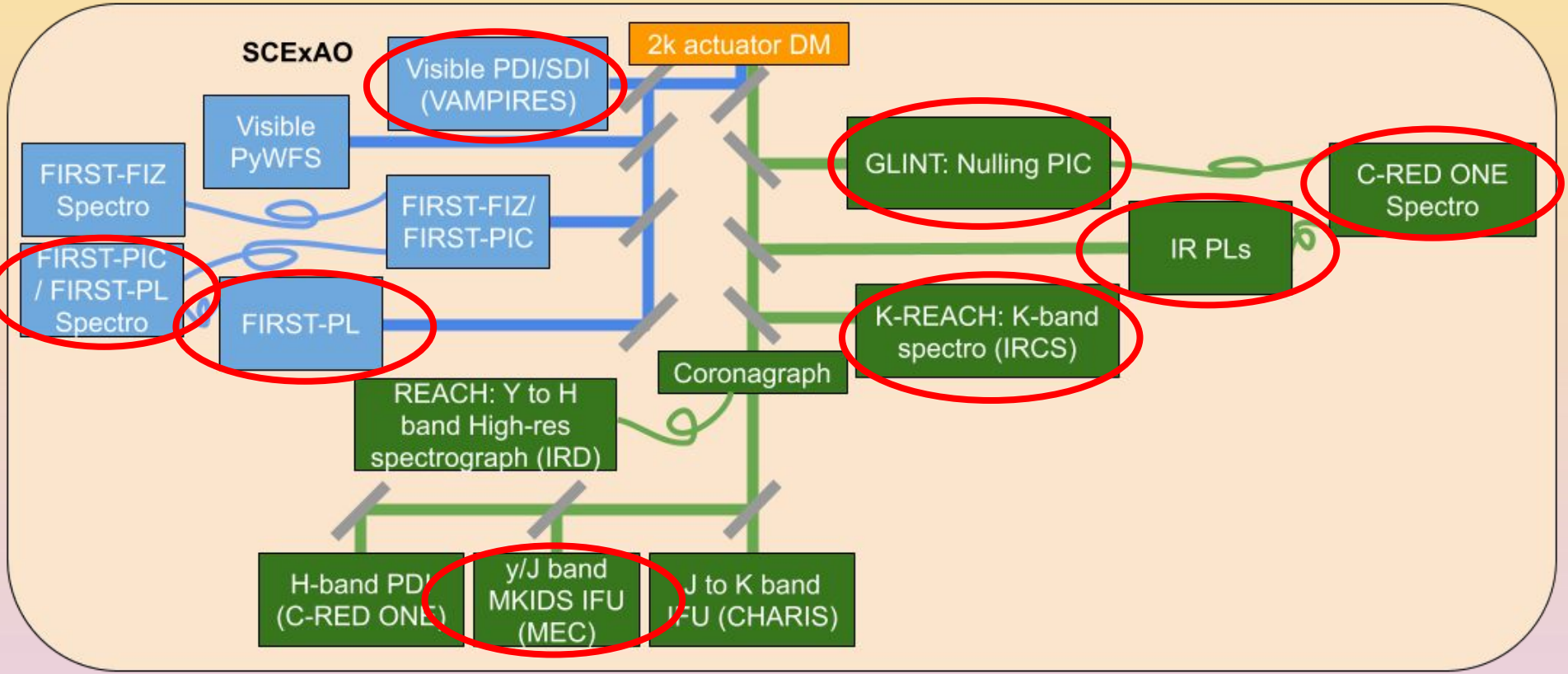




IEFC: improve the contrast

SCExAO upgrades

SCExAO is constantly evolving. We are pushing for better wavefront control, as well as visible/IR photonics developments.



Next steps: SCExAO v4.0?

- We will improve WFC of AO3k and SCExAO with automatic gains, machine learning, LWE correction
- SPIDERS showed that AO3k is good enough so that we can focus on dark hole digging and stabilization with SCExAO
- We will upgrade the SCExAO BMC 2k DM to a BMC Hex-3k DM (end of 2026)
  - More actuators is more better
  - The segmented DM will allow us to perform relevant tests for TMT and HWO.
- We end up with a free 2k DM but no electronics
  - We can buy new electronics (cheap…)
  - Replace a fold mirror with the 2k DM for 2 DM control
- CHARIS v2?
  - LEONARDO's detector developments are promising, with Ike Pono, a 1kx1k HgCdTe detector
  - Hopefully a 2kx2k detector drop-in replacement to the HAWAII2RG in the future